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Two centre effects in ionization of atomic hydrogen by antiproton impact

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Abstract . When an atom is ionized by ion impact, the electron is ejected into the final continuum state of a two centre potential due to Coloumb fields of the projectile and residual target nucleus. The electron in this state should not be represented by simply a plane wave due to the long range nature of Coloumb potential In the present article, an attempt has been made to study the electron ejected spectra in antiproton hydrogen collisions The calculation to obtain doubly differential cross section is made by employing a continuum state wave function [1] which incorporates distortion due to the Coloumb fields of both the projectile and target nucleus

Keywords Atomic hydrogen, doubly differential cross section

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Single ionization in ion-atom collisions has been studied for many decades since the first detailed calculations of total ionization cross sections (TICS) for proton hydrogen system by Bates and Griffings [2] using first Born Approximation (FBA). To get a deeper insight into the electron emission process it is more useful to study doubly differential cross sections (DDCS). The first absolute measurements for DDCS were carried out by Rudd and Jorgensen [3] and Rudd *et al* [4] for electrons ejected from He and H_2 targets by proton impact.

Electron emitted from atoms by ion impact in general, shows for a fixed emission angle, a continuous monotonically decreasing energy distribution. However, for certain ejection angles, maxima in DDCS have been found in the energy distribution spectra in the case of proton-hydrogen collision [1]. A brief discussion of the same may be useful in the study of energy distributions of emitted electron in antiproton-hydrogen collision.

The maximum in DDCS at electron velocities $v_e \equiv 0$ is called soft collision region. At very small ejection angles, a peak appears when the projectile velocity (v_p) nearly equals to the ejection electron velocity. This cusp shaped peak was observed in the energy spectra for the first time by Crooks and Rudd [5] and is called electron capture to continuum (ECC) peak and as the angle increases the peak disappears. For angles smaller than 90° another structure appears known as binary encounter peak (BEP) around electron velocity $2v_p \cos(\theta)$. The BEP arises from a head-on collision between the projectile and the electron.

According to Bethe-Born approximation, the ionization cross section for charged particle impact depends upon the collision velocity and square of the projectile charge. As such within this framework the cross section for equivelocity proton and antiproton should be identical. For sufficiently high collision velocity this is indeed true. However, for smaller collision velocities there exists marked difference in total and differential cross section for protons and antiprotons. So it became necessary to study the behaviour of emission spectra in the simultaneous presence of attractive target and repulsive Coloumb potential.

The first calculation with antiprotons as projectile were performed by Garibotti and Miraglia [6] considering the electrons emitted in forward direction. Similar study was done by Brauner and Briggs [7] for electron and positrons as projectiles. They reported that in the region of ECC peak the negative charge projectiles showed a pronounced dip. Later Fainstein *et al* [8] studied DDCS for 300 keV proton and antiproton impact on atomic He as a function of ejection energy for $\theta = 0°$ and 10°. For the case of proton impact, the ECC peak is observed when $\theta = 0°$ and at 10° only a hump remains and in antiproton case a dip appears in forward direction and the feature continues even up to larger angles. However, the dip disappears as angle increases. This behaviour is well known from the measurements of Rudd *et al* [4] and calculations of Salin [9].

For the description of exponential dip that arises in case of antiproton impact on atomic hydrogen we produce the ejection spectra at an ejection angle of 1° in Figure 1 for 70 keV projectile energy and compare the present computed results with the previously calculated results of proton hydrogen system [1]. For 70 keV projectile energy one obtains the equivelocity electron energy about 38 eV following the relation

$$\frac{1}{2} m v_e^2 \times 27.2 = Eb \,,$$

where

$$v_p = \sqrt{\frac{En}{1.8361 \times 13.6}}$$

and *En* and *Eb* are respectively the incident and ejection energy in (eV).

The sharp exponential dip in DDCS occurs at the ejection energy of 38 eV which is analogous to the results of Fainstein *et al* [8] and the dip is positioned at the same ejection energy where ECC peak was found for proton hydrogen collision. The dip remains an important feature at 30° as shown in Figure 2.

A brief description of the continuum state wave function [1] will be useful for the study of the present antiproton hydrogen case. The wave function ψ_{kc}^{-} takes the form

$$\psi_{kc}^{-} = N_1 N_2 e^{i\mathbf{k}.\mathbf{r}} \times {}_1F_1\left(i\alpha_p, 1; -i\left(k_p r_p + \mathbf{k}_p.\mathbf{r}_p\right)\right) \times {}_1F_1\left(i\alpha_T, 1; -i\left(k_T r_T + \mathbf{k}_T.\mathbf{r}_T\right)\right) \times \exp\left(-ik^2 t/2\right)$$

where $\alpha_p = -\frac{Z_P}{k_{pe}}$ and $\alpha_T = -\frac{Z_T}{k_{Te}}$; Z_p and Z_T are the charges of the projectile and target respectively ; k_{P_e} and k_{T_e} are the velocities of electron in the projectile and target frame of reference and all values are in atomic units $(e = \hbar = m = 1)$. Then

$$N_1 = e^{-\pi\alpha_p/2}\Gamma\left(1+i\alpha_p\right),\quad N_2 = e^{-\pi\alpha_T/2}\Gamma\left(1+i\alpha_T\right).$$

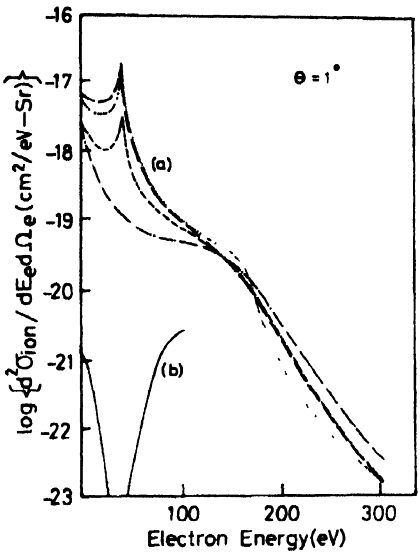

Figure 1.

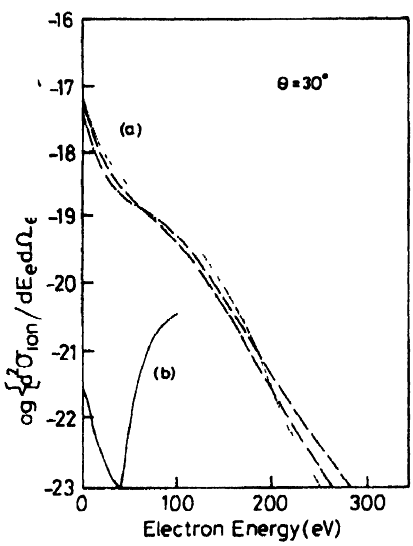

Figure 2.

Figure 1. Doubly differential cross section as a function of electron energy for ejection angle of 1° for the ionization of atomic hydrogen in ground state by proton impact (previously calculated (Ref [1]) (a) and antiproton impact (b)

(a) Sahoo *et al* [Ref 1] . (....) , Born [11] (—— ——) , CDW-EIS [11] . (--------) CTMC [11] . (— — - -)

(b) Present result (__________)

Figure 2. Doubly differential cross section as a function of electron energy for ejection angle of 30° for the ionization of atomic hydrogen in ground state by proton impact (previously calculated (Ref. [1]) (a) and antiproton impact (b)

(a) Sahoo *et al* [Ref 1] (. ...) ; Born [11] (---- ----) ; CDW-EIS [11] (— — - -)

(b) Present result . (__________)

Now, the exponential dip in the case of antiproton impact is attributed to the fact that the electron ejection cross section depends on the density of states popularly known as Coloumb factor $\left(N_1 = \exp(-\pi\alpha_p/2)\,\Gamma(1+i\alpha_p)\right)$ and its square appears as a factor in the cross section as,

$$\left|N_1\right|^2 = \left|\exp(-\pi\alpha_p/2)\,\Gamma(1+i\alpha_p)\right|$$

$$= \exp(-\pi\alpha_p) \times \frac{\pi\alpha_t}{\sinh\pi\alpha_t}$$

$$= 2\pi\alpha_p \times \frac{\exp(-\pi\alpha_p)}{\exp(\pi\alpha_p) - \exp(-\pi\alpha_p)}$$

$$= \frac{2\pi\alpha_p}{\exp(2\pi\alpha_p) - 1}.$$

Now, for a negatively charged particle,

$|N_1|^2$ reads

$$\text{if } Z_p < 0, \qquad \lim_{k_{-} \to 0} |N_1|^2 \to 2\pi\alpha_p \exp(-2\pi\alpha_p) \to 0$$

and gives rise to the singular structure that leads to an exponential dip in the cross section.

For a positively charged particle,

$|N_1|^2$ reads

$$\text{if } Z_p < 0, \qquad \lim_{k_{-} \to 0} |N_1|^2 \to -2\pi\alpha_p$$

and gives rise to a sharp peak in the cross section called ECC peak.

Thus, ECC peak originates in the long range behaviour of the attractive Coloumb potential which produces a divergence in the continuum density of states near the threshold. For repulsive Coloumb potential, the divergence in the density of states of the attractive case is replaced by a zero density. This makes the cross section exactly zero when the electron velocity in the projectile frame is zero, for antiproton impact [10]. The sign of the projectile charge contained in the Coloumb factor is responsible to produce different structure in DDCS. The dip in DDCS for antiproton impact can be considered as two centred electron emission (TCEE) effect. In particular, the role of two centre effects has been found to be quite significant in ion-atom collisions, manifesting certain features of the spectra of ejected electron. These arise since in post collisional regime the ionized electron experiences interactions with both the residual target core and the projectile with nearly equal footing.

The FBA could not account for this effect because in this model, the interaction is only considered as perturbation which produces transition of electron from a bound state to continuum state of the target atom and is valid for short range potentials and not for the case of long range potential where the ejected electron moves under the influence two Coloumb potentials (projectile and residual target). Due to long range character, Coloumb potentials distort the unperturbed wave function even when the two centers are very far apart. In the present procedure, the electron is considered to move under the influence of the projectile and residual target and incorporates the distortion to a certain extent. The present computed results thus may be comparable with the results obtained by using other perturbative treatments.

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References

[1] S Sahoo, K Roy, N C Sil and S C Mukherjee *Phys Scripta* **58** 126 (1998)

[2] D R Bates and G Griffings *Proc Phys Soc.* **A66** 961 (1953)

[3] M E Rudd and T Jorgensen Jr. *Phys Rev* **131** 666 (1963)

[4] M E Rudd, L H Toburn and N Stolterfoht *At Data Nucl Data Tables* **18** 413 (1976) , **23** 405 (1979)

[5] G B Crooks and M E Rudd *Phys Rev. Lett.* **25** 1599 (1970)

[6] C R Garibotti and J E Miraglia *Phys Rev.* **A21** 572 (1980)

[7] M Brauner and J Briggs *J Phys* **19** L325 (1986)

[8] P D Fainstein, V H Ponce and R D Rivarola *J Phys* **B21** 2898 (1988)

[9] A Salin *J Phys* **B5** 979 (1972)

[10] P D Fainstein, V H Ponce and R D Rivarola *J Phys* **B24** 3091 (1991)

[11] D R Schultz, R E Olson, C O Reinhold, M W Gealy, G W Kerby, Y Y Hsu and M E Rudd *J Phys.* **B24** L599 (1991)